Improved GaN Growth on Nanoporous Substrates

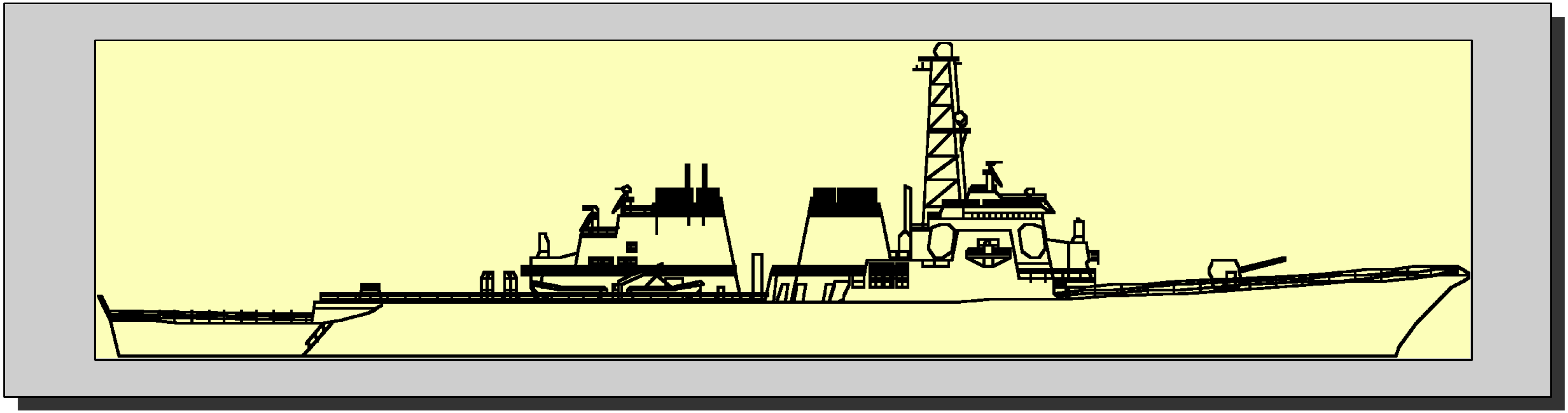
D.D. Koleske, J.A. Freitas, Jr., G.C.B. Braga*, A.E. Wickenden, R.L. Henry, S.C. Binari, M.E. Twigg, J.C. Culbertson, M. Fatemi, P.B. Klein, M. Mynbaeva**, and V.A. Dmitriev***

Naval Research Laboratory, Washington, D.C. 20375, USA,
*Inst. Of Physics, Dept. of Brasilia, Brazil.
**Ioffe Physical-Technical Institute, St.Petersburg, Russia.
***TDI Inc., Gaithersburg, MD, USA.

Support from the Office of Naval Research

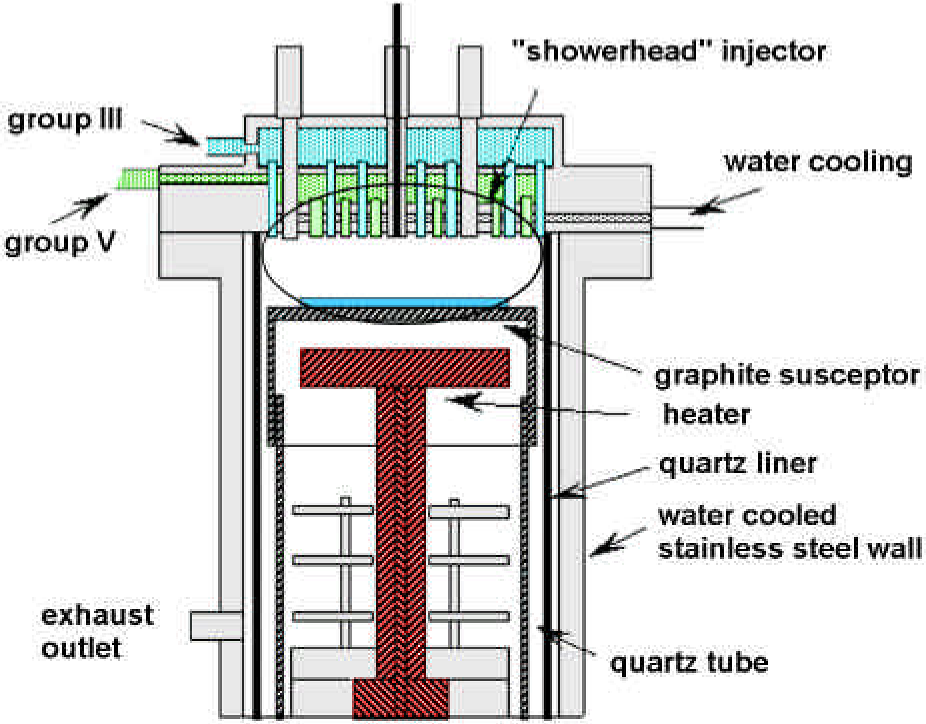
DARPA Meta-Materials Workshop, Sept 29th 2000

Navy Needs for Wide-Bandgap Semiconductors



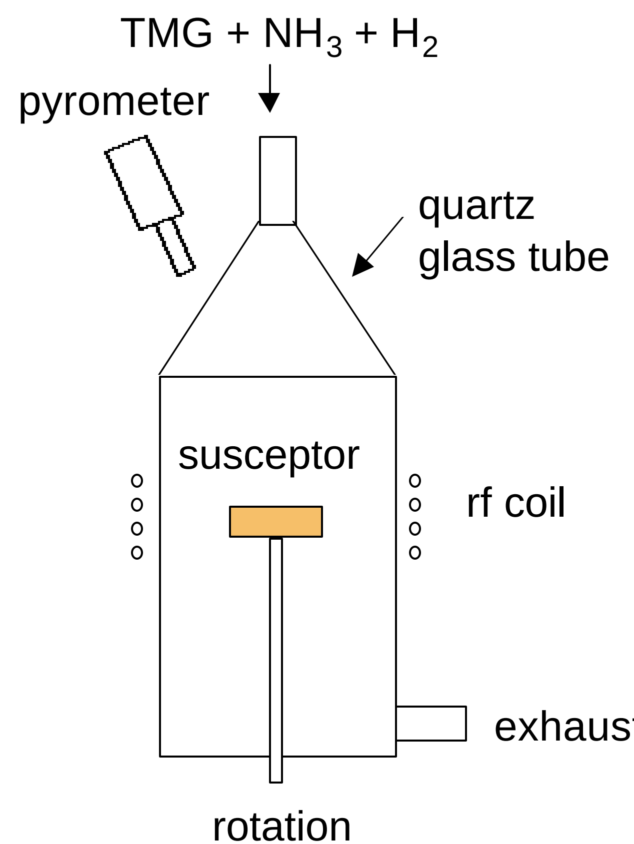
- RF applications: radar transmitters
- High power switches: all-electric ship
- High temperature applications: engine sensors
- High radiation tolerance: space applications, nuclear reactors
- Optoelectronics: communications

Two Nitride MOVPE Reactors at NRL



Advantages quartz rf-heated

- Higher growth rates
- Increased flexibility
- Better nucleation layers
- Higher temperatures possible



Advantages close-spaced showerhead

- Avoid pre-mixing of alkyls and NH_3
- Fixed boundary layer
- More uniform film growth
- Large grain size
- Better high temperature growth

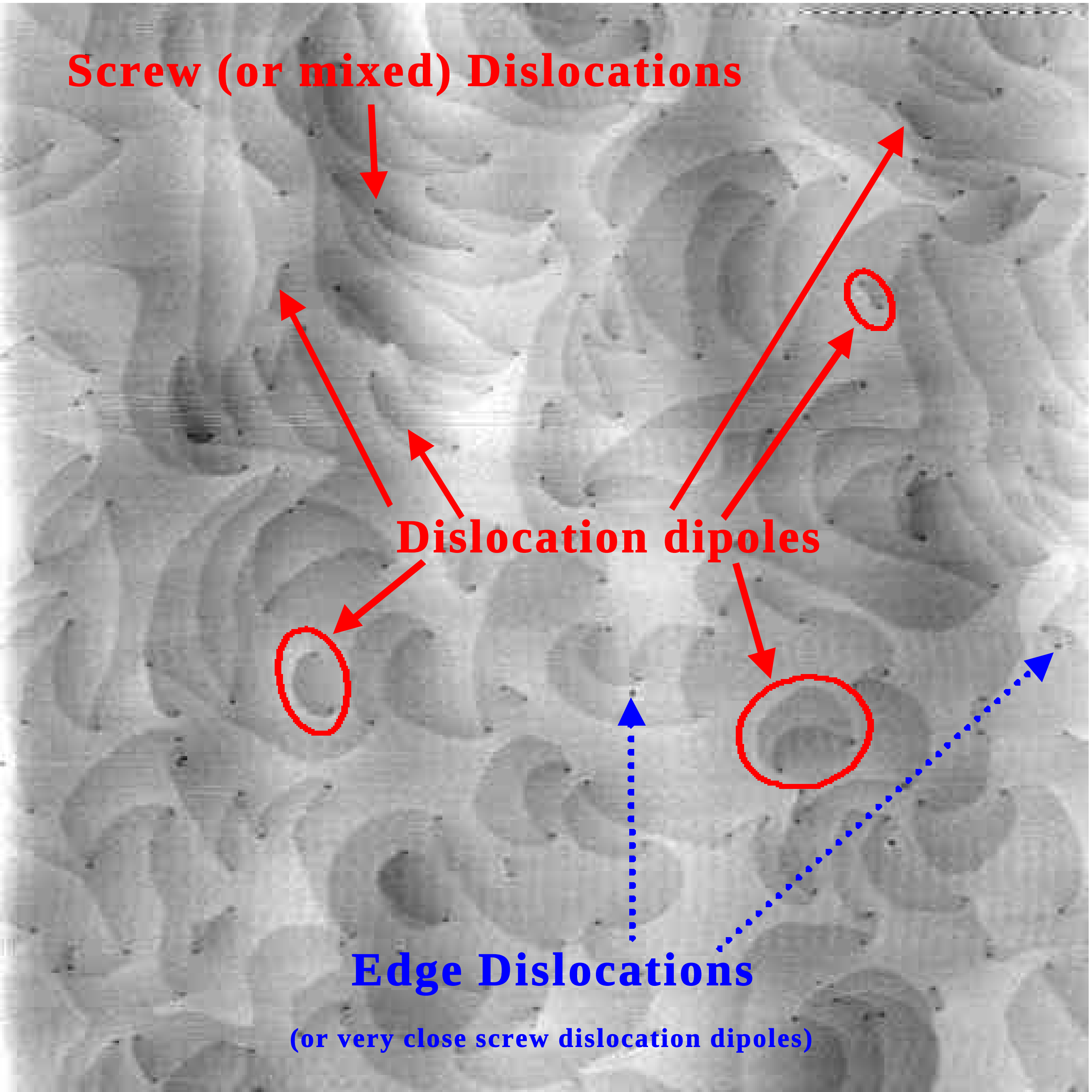
Group III-Nitride Research at NRL

- **MOCVD growth**
  - Two nitride reactors, experimental and theoretical studies.
- **Characterization**
  - Electrical analysis
    - » Hall transport, Current-Voltage, bulk resistivity measurement.
  - Microstructural analysis
    - » Transmission Electron Microscopy (TEM), Atomic Force Microscopy (AFM), X-ray Diffraction (XRD).
  - Spectroscopic analysis
    - » Photoluminescence (PL), Magnetic Resonance (EPR, ODMR), Cathodoluminescence (CL).
- **Device Fabrication**
  - Microwave transistors and diodes fabrication and testing.

Methods for Reducing Dislocations in GaN

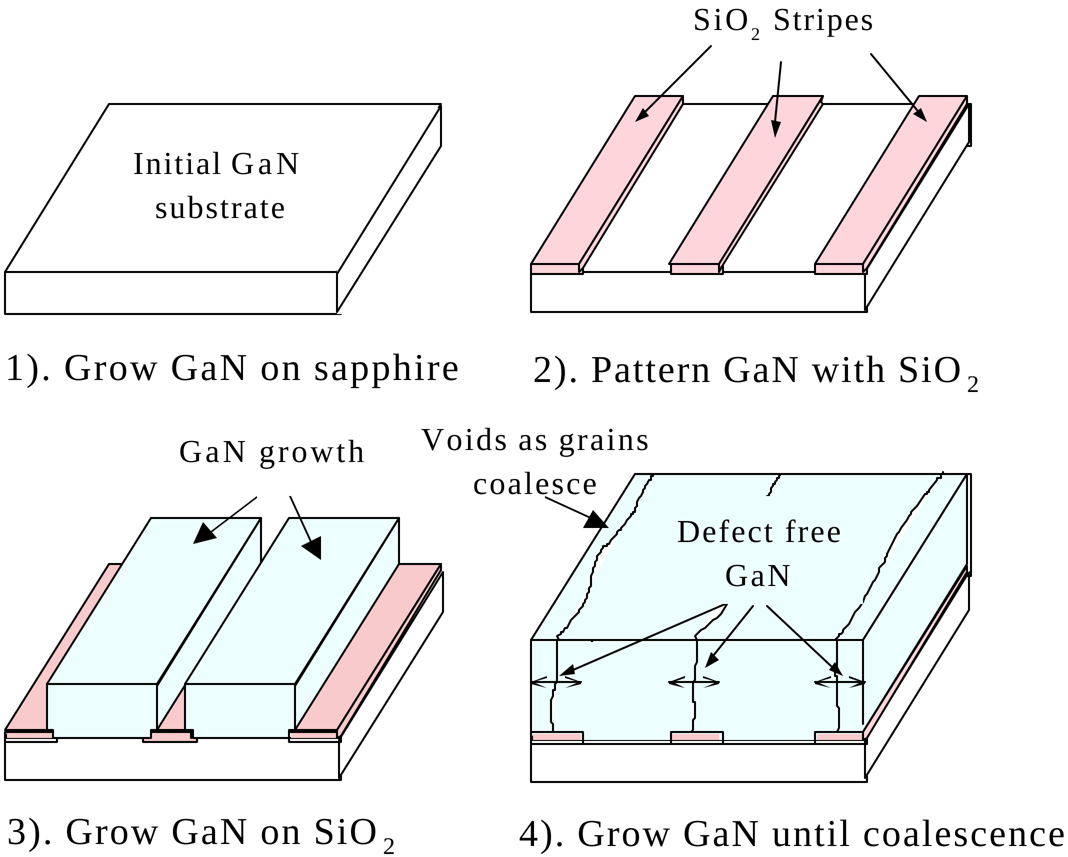
- Homoepitaxy on GaN single crystals.
  - Bulk crystals not commercially available.
- Lateral Epitaxial Overgrowth (LEO).
  - Lateral growth over a oxide or nitride mask region.
- “Pendeoepitaxy”.
  - Lateral and vertical growth from an etched GaN post.
- Interlayers - regrowth of nucleation layer
  - Removes screw-like dislocations from GaN.
- GaN growth on “Nanoporous” Material.
  - GaN films are electrochemically etched and GaN is regrown in the pores.
  - GaN films are grown on as-grown “porous” AlN layers.

AFM of MOCVD GaN on Sapphire

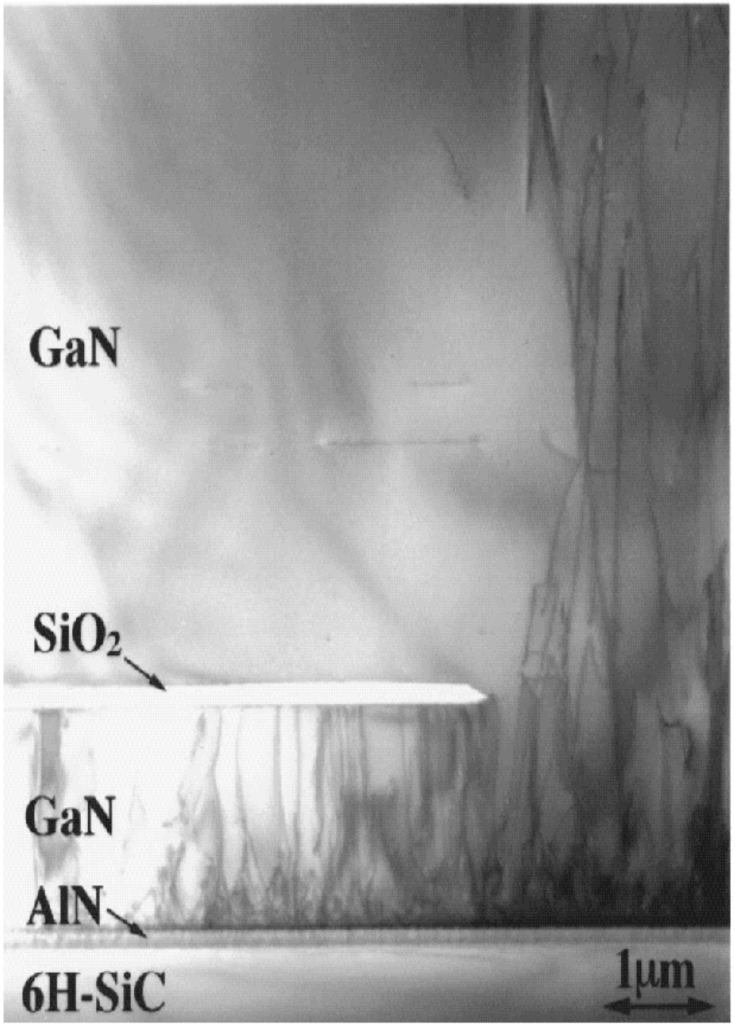


- Observe lattice step edges.
  - Most step edges are ~2Å.
  - Ga planes and N planes are separated by ~2Å.
- Lattice step edges terminate in pits (**Þ screw or mixed dislocations**).
  - Each pit has a full ~5Å Ga to Ga or N to N lattice step as you go around it.
  - The intermediate plane is not always seen.
- Dislocation density ~$8\times10^{8}/\mathrm{cm}^{2}$

GaN Lateral Epitaxial Overgrowth (LEO)



O. Nam et al. Appl. Phys. Lett. 71, 2638 (1997)

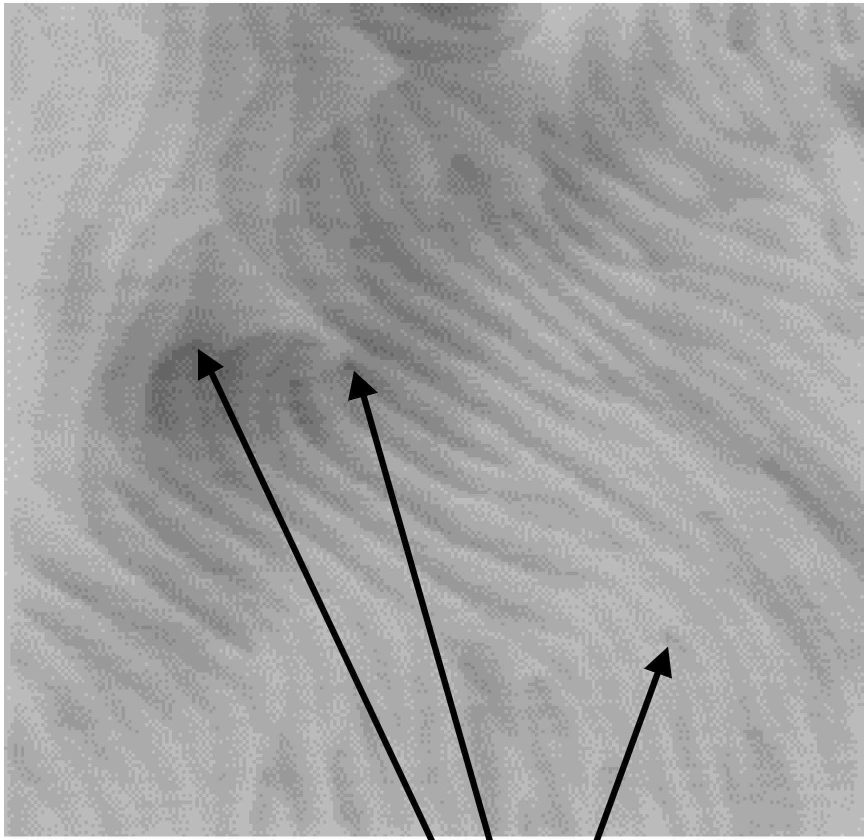


Advantage: Reduces dislocations in LEO region.

Disadvantages: Requires lithographic patterning, material not uniform.

AFM Observation of Defect Reduction in LEO GaN

Bulk GaN 10^8-10^{10} dislocations

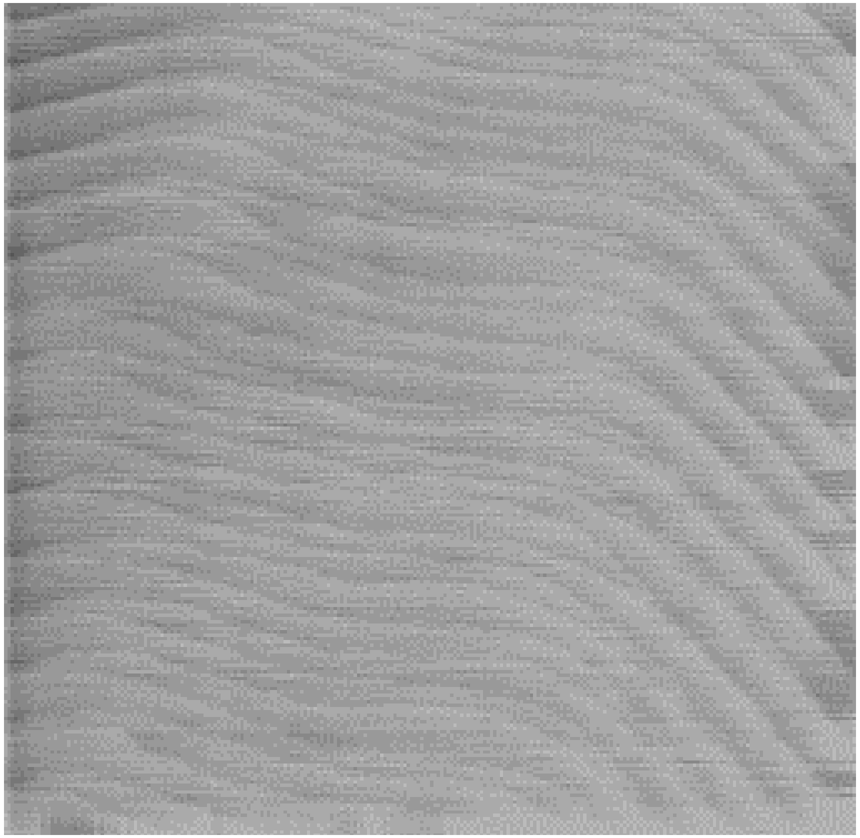


2 µm x 2 µm

step terminations

Several screw dislocations in Bulk

LEO GaN < 10^6-10^7 dislocations

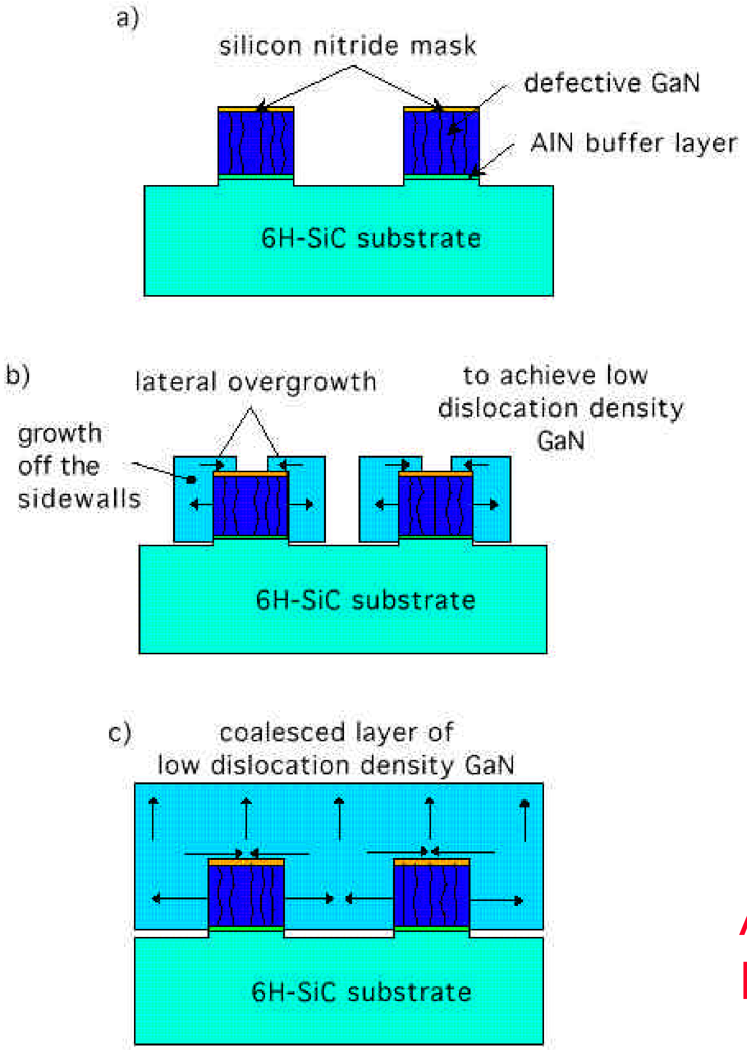


2 µm x 2µm

no step terminations

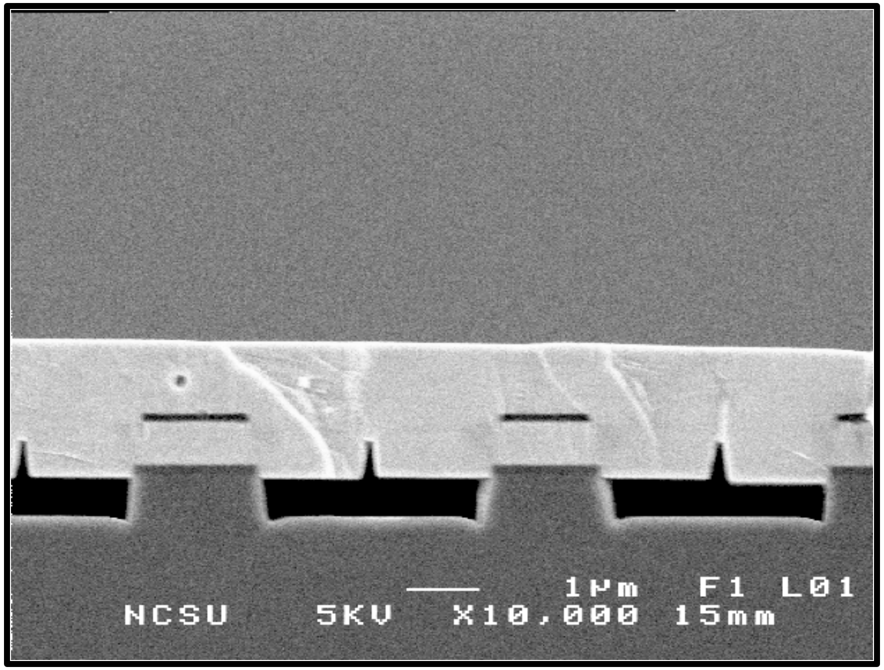
no dislocations in LEO

GaN Pendeoepitaxy for Dislocation Reduction



"pendeo" growth process

T. Gehrke et al., See http://muriserver.mte.ncsu.edu/muri-8.htm Report on ONR MURI on Compact Power Supplies Based on Heterojunction Switching in Wide Band Gap Semiconductors,

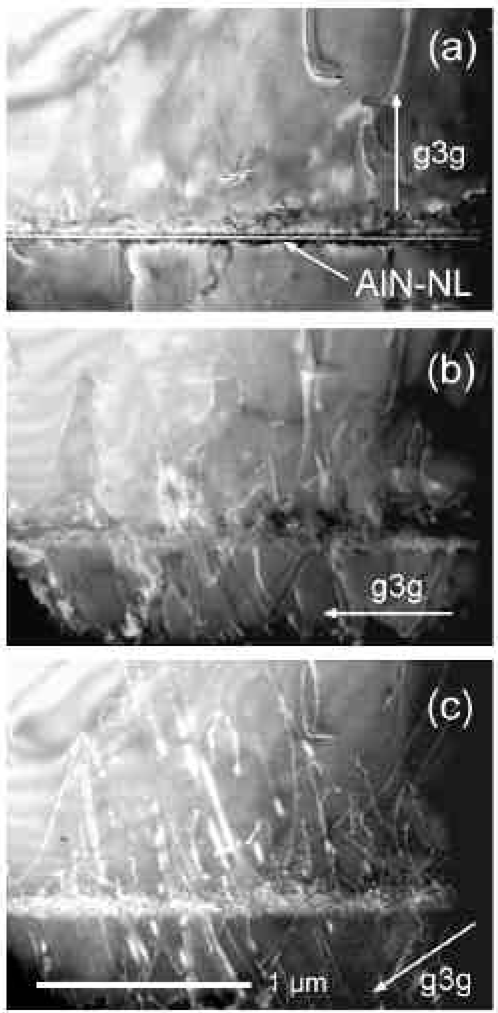


Advantage: Reduces most dislocations in GaN. Material more uniform.

Disadvantage: Requires lithographic patterning and RIE etching step. Stress in GaN film.

AlN Interlayers to Improve Bulk GaN

D.D. Koleske, et al. Appl. Phys. Lett, Nov 15th 1999, also MRS Fall 1999, Symposium O, talk 7.3

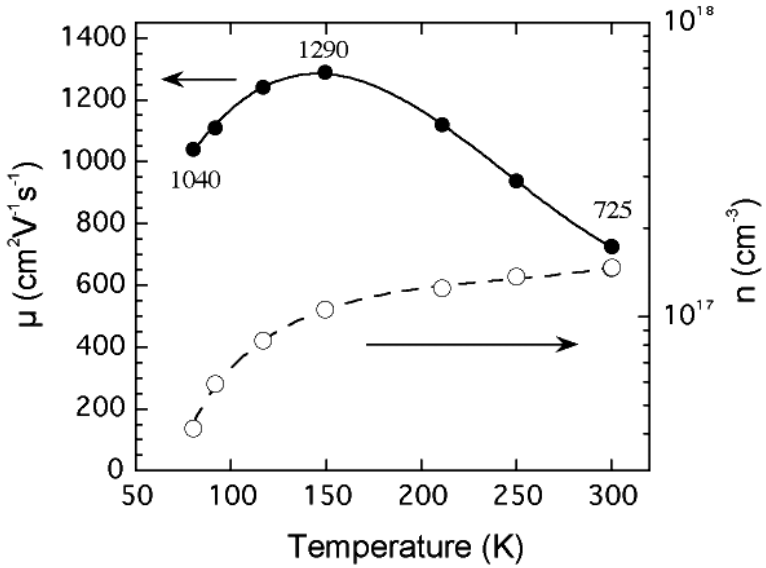


The interlayer is a regrowth of the AlN nucleation layer on GaN. This process can be repeated a number of times to reduce the dislocation density and provide thick GaN films on sapphire without cracks.

Using the interlayer screw-type dislocations are filtered out of the growth process

Without interlayers, $\mu = 440\ cm^2/Vs$, with $\mu = 725\ cm^2/Vs$

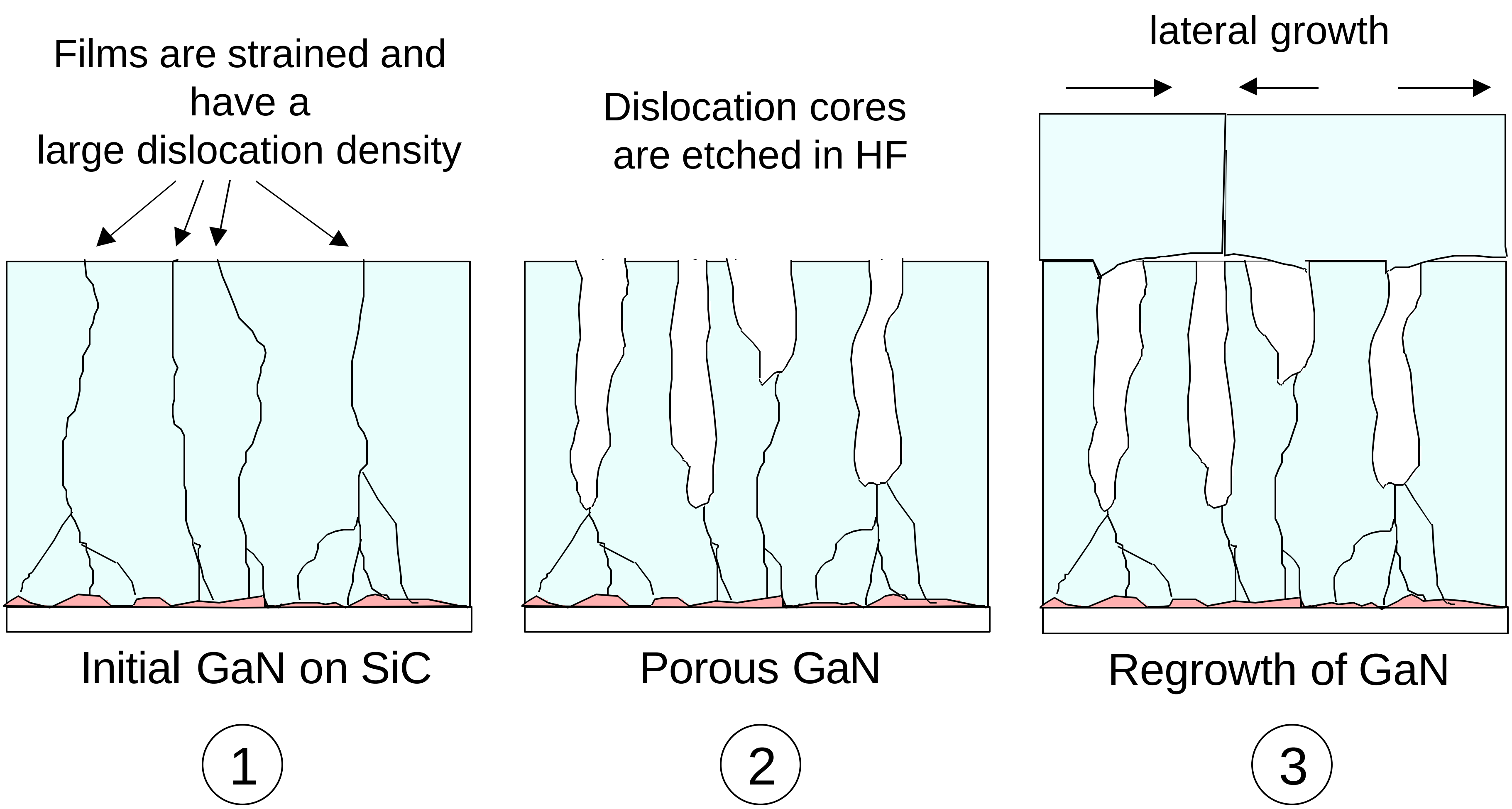
Carriers behave as bulk GaN carriers and not 2DEG carriers



Work in progress to incorporate interlayers into HEMT devices to further improve device performance

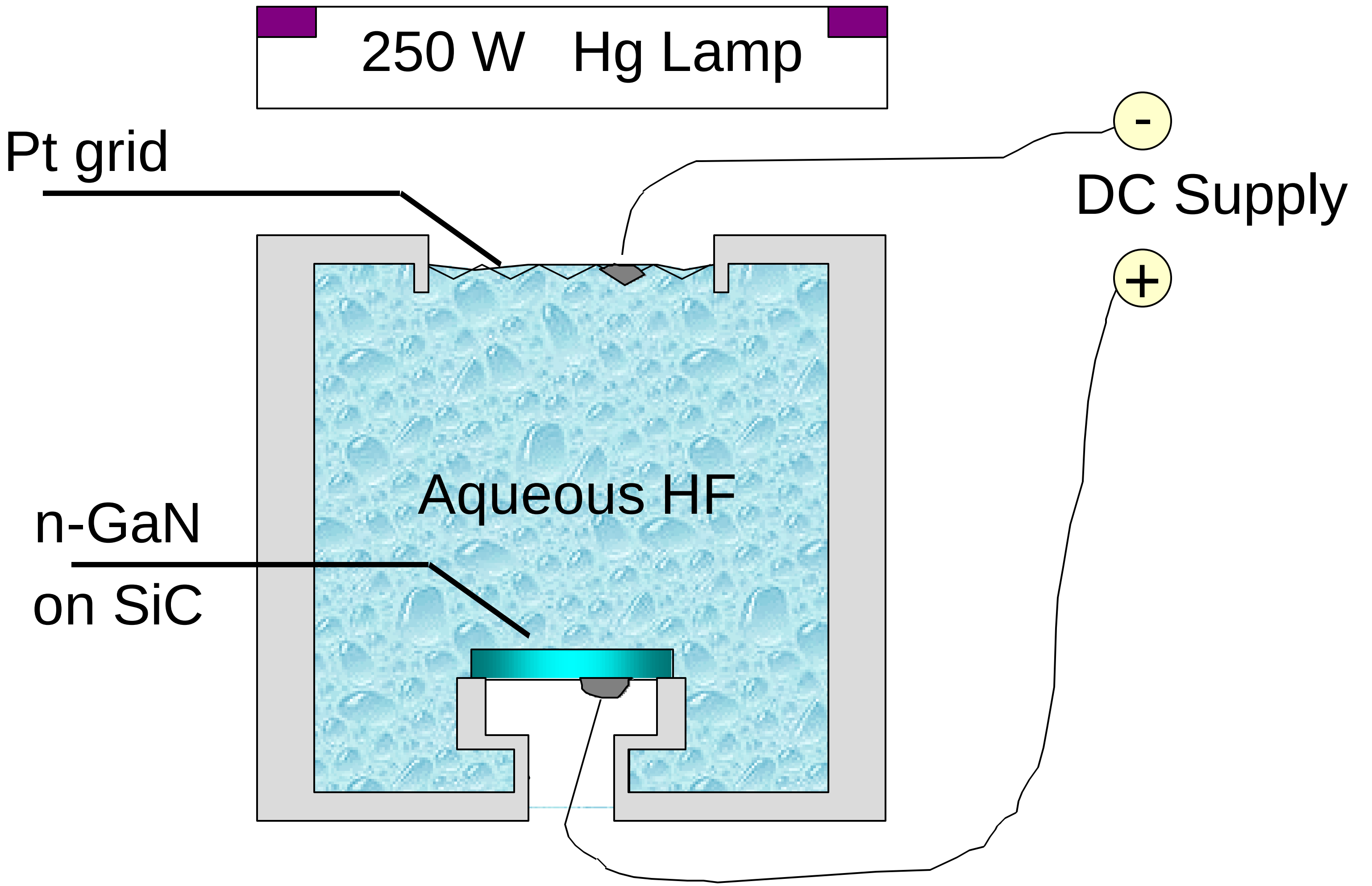
GaN Growth on Nanoporous GaN

GaN growth mechanism is likely similar to "pendeoepitaxy" where lateral growth proceeds from etched GaN pillars



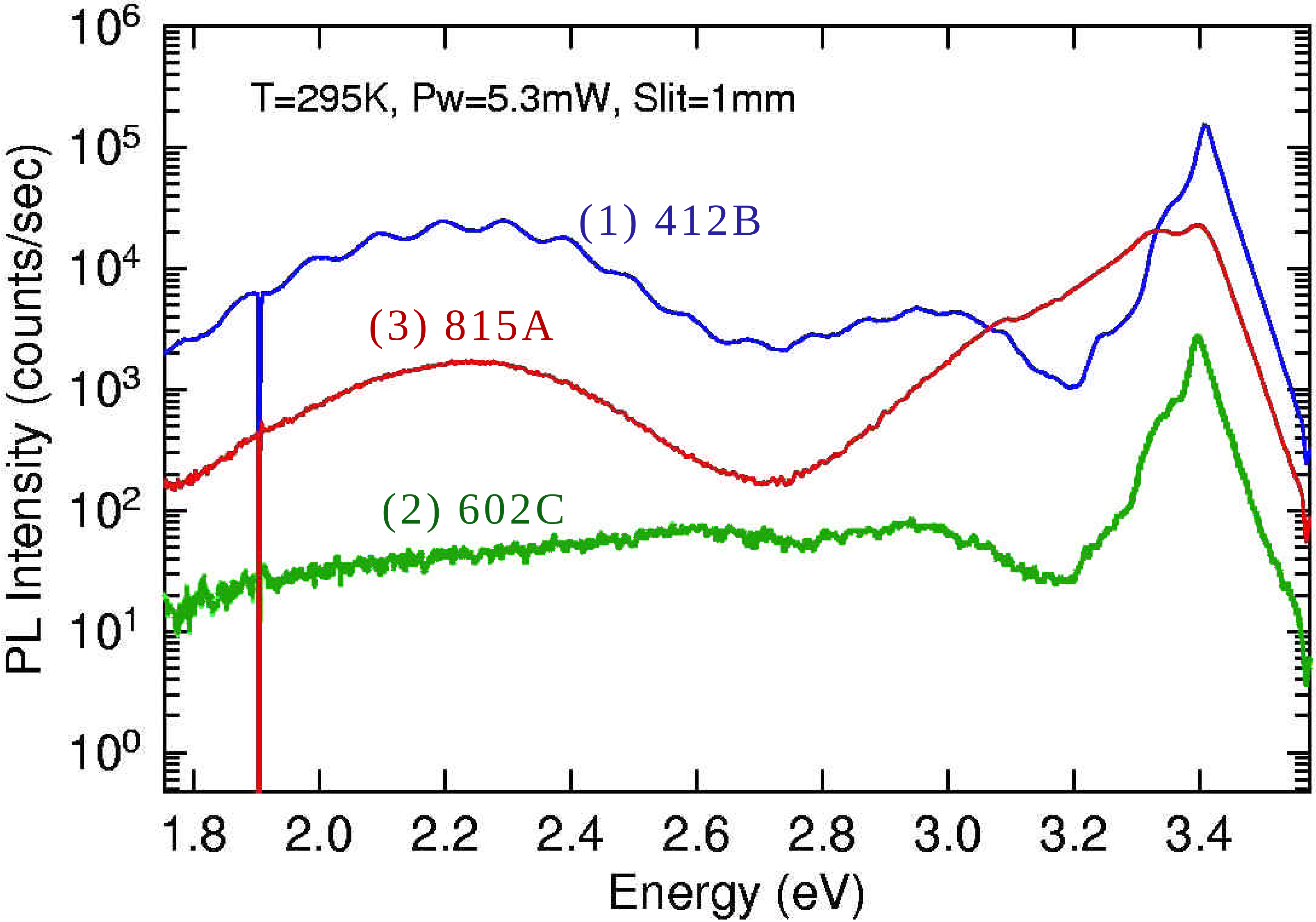
Making GaN Porous

M.G. Mynbaeva and D.V. Tsvetkov, Inst. Phys. Conf. Ser 155, p 365 (1996).



Room Temperature Photoluminescence

of GaN on porous GaN

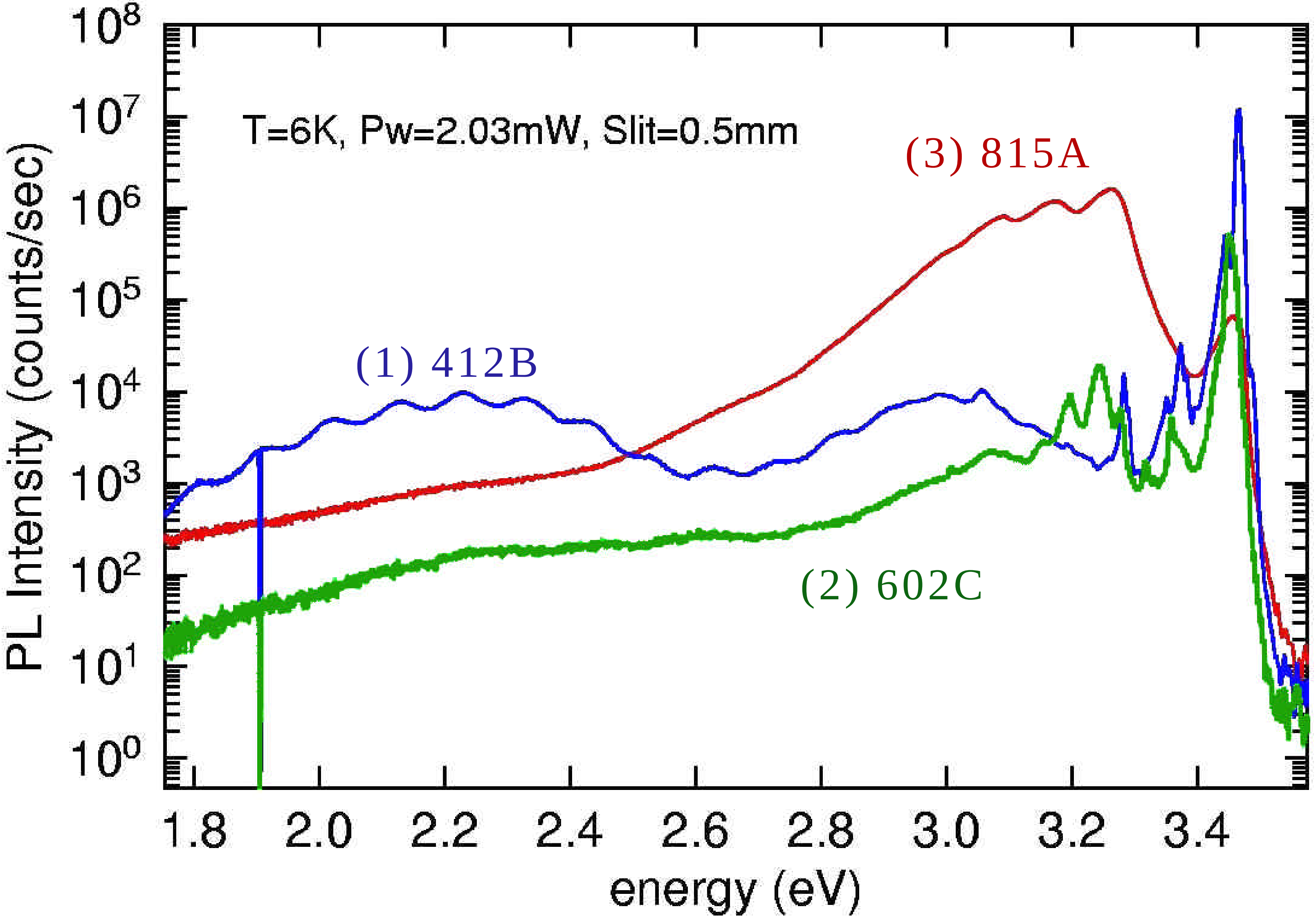


Room Temperature Photoluminescence

- 1) 412B - grown at 76 torr
  - Yellow (2.2 eV) and blue (3.0 eV) bands dominate the lower energy spectral region.
- 2) 602C - grown at 130 torr (best growth pressure)
  - In general, PL emission at high temperature in high quality material is dominated by band-to-band and free exciton recombination processes, which is observed in this sample.
- 3) 815A - grown at 200 torr
  - Dominated by yellow band and a broad emission comprising the free-to-bound and band edge transitions.

Low Temperature Photoluminescence

of GaN on porous GaN

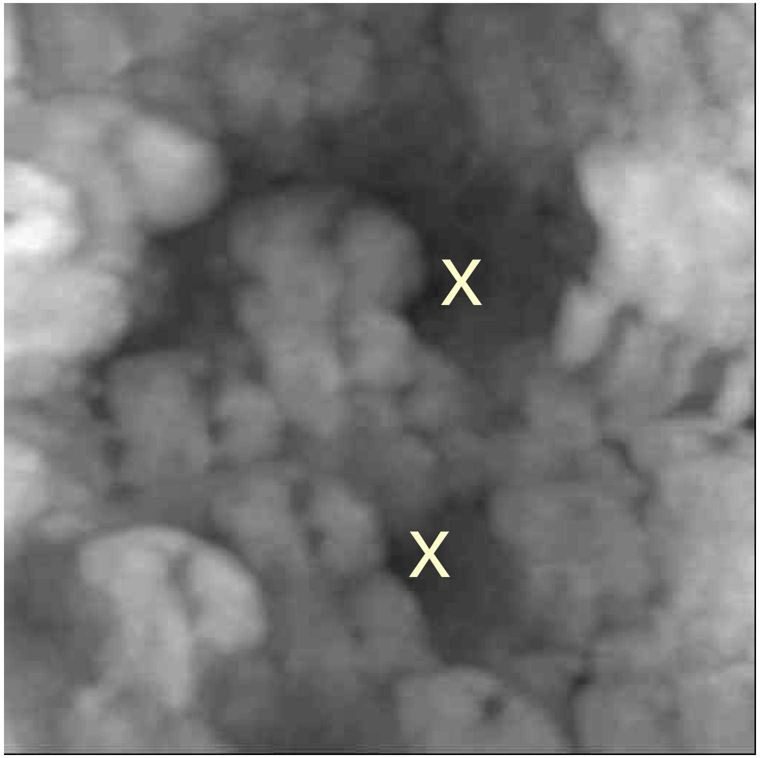
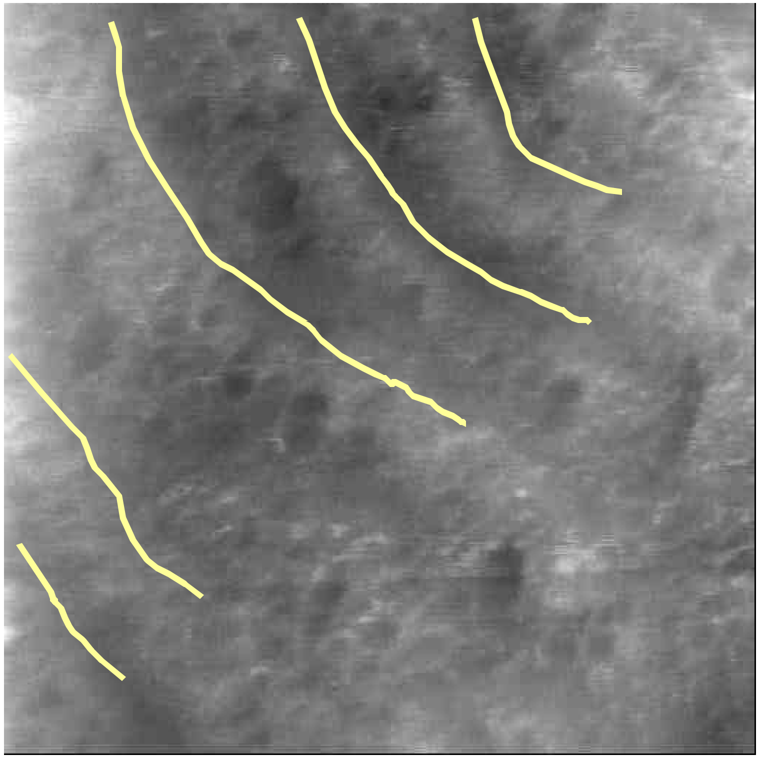


Low Temperature Photoluminescence

- 1) 412B - grown at 76 torr
  - Observe yellow (2.2 eV) and blue (3.0 eV) bands.
  - Yellow band may be structural and/or impurity related.
  - Blue band is a compensating center which maybe related to carbon. The blue band is usually observed in highly-resistive (semi-insulating) GaN
- 2) 602C - grown at 130 torr (best growth pressure)
  - Lower yellow band by a factor of 100.
  - Lower blue band by a factor of 10.
- 3) 815A - grown at 200 torr
  - Higher compensation of background donors by an (as yet) unidentified shallow acceptor.

AFM of porous GaN and GaN regrowth

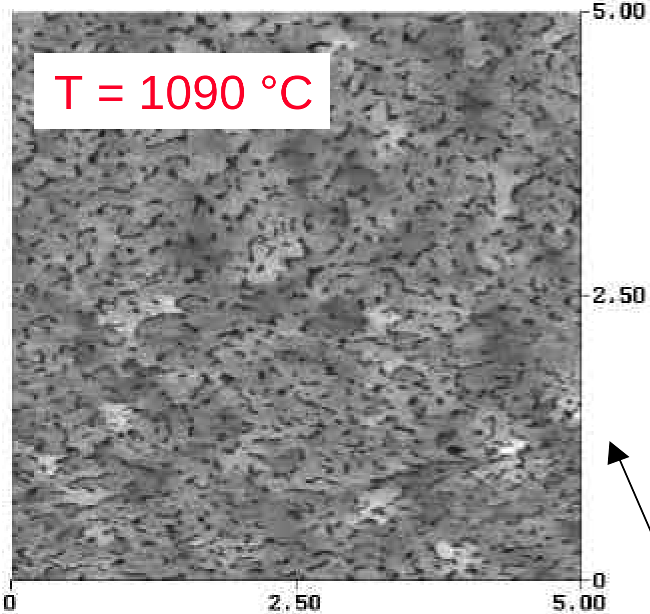
1x1 µm scans

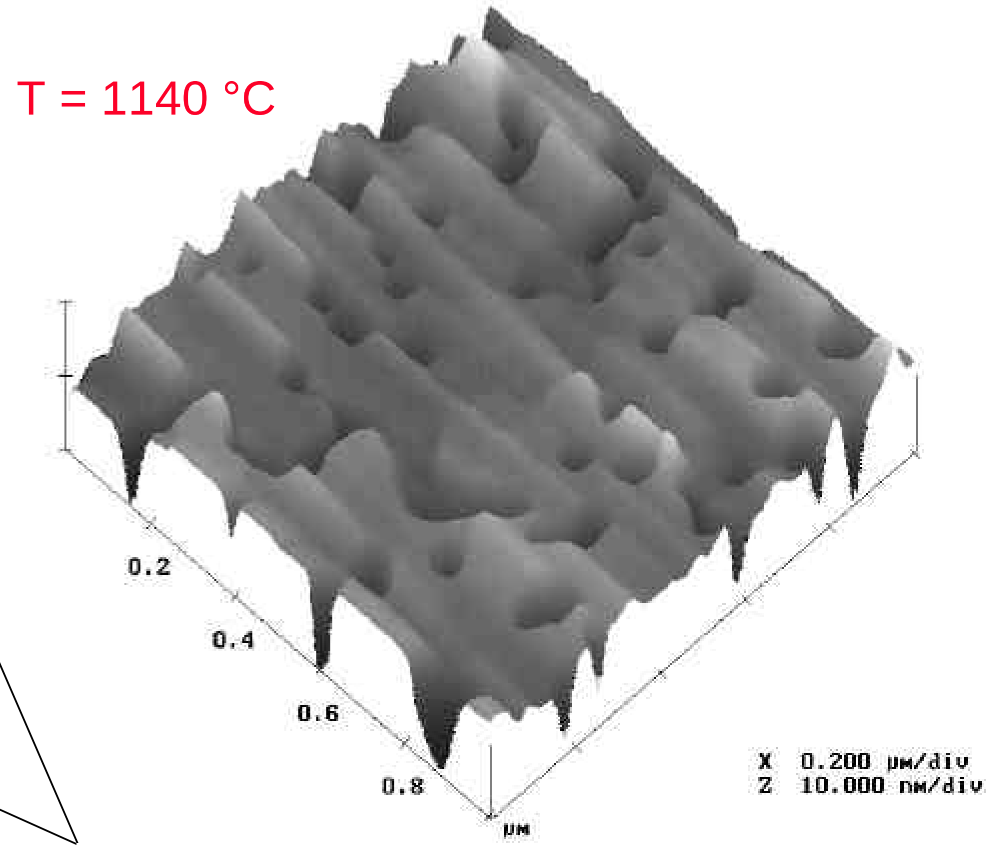
Initial porous substate	2 µm GaN on porous substrate
	
height scale 0-10 nm rougher x = potential nucleation site?	height scale 0-3 nm smoother yellow lines = step edges = 5 Å

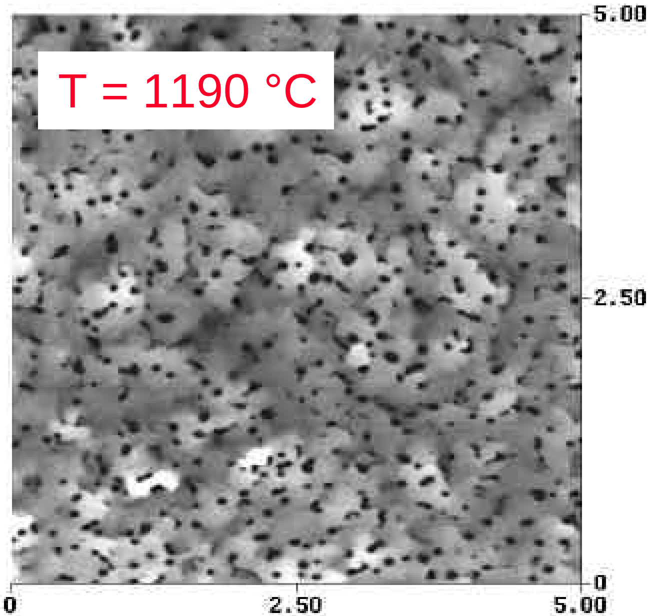
James Culbertson
Code 6876
22 September 2000

AFM of “Porous” AlN on SiC

AlN on SiC has pores

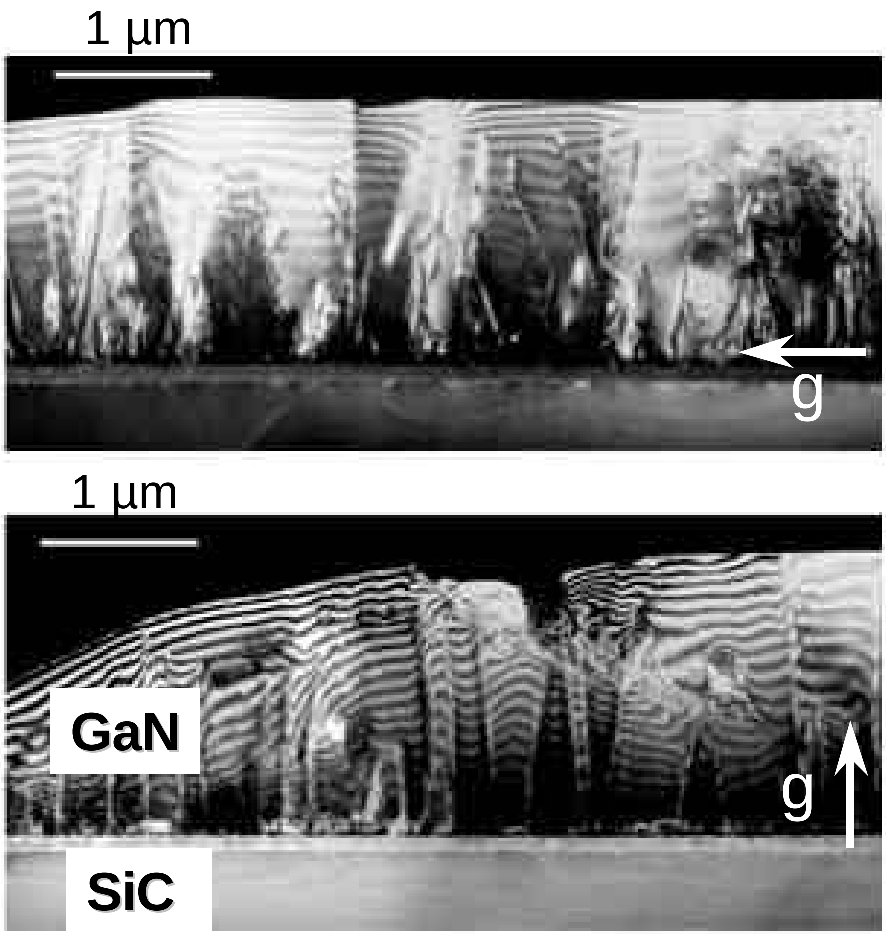




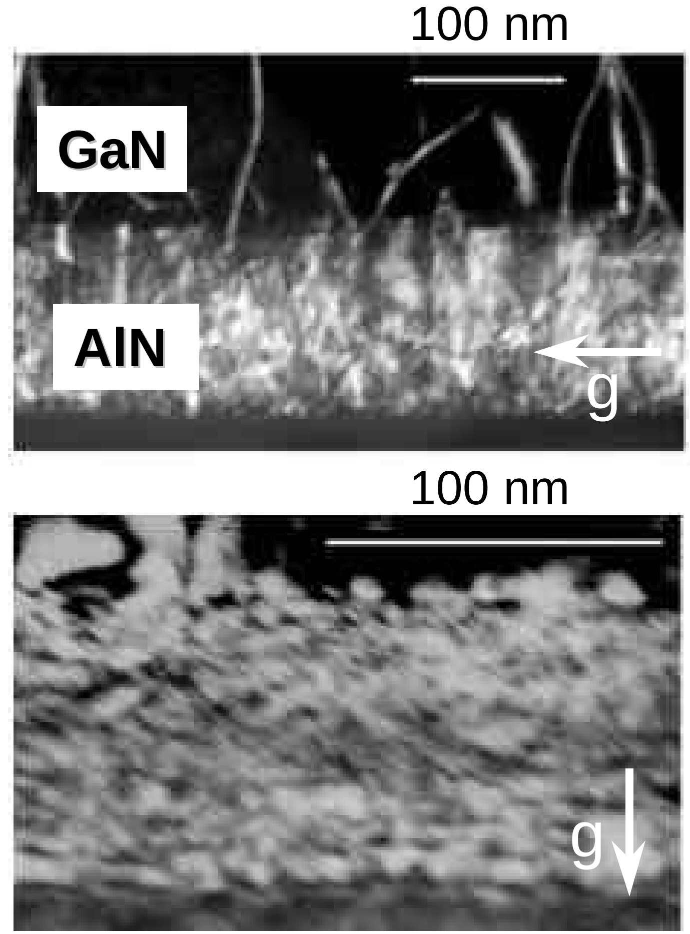


Pore spacing can be controlled by MOVPE growth temperature

TEM of GaN on “porous” AlN on SiC

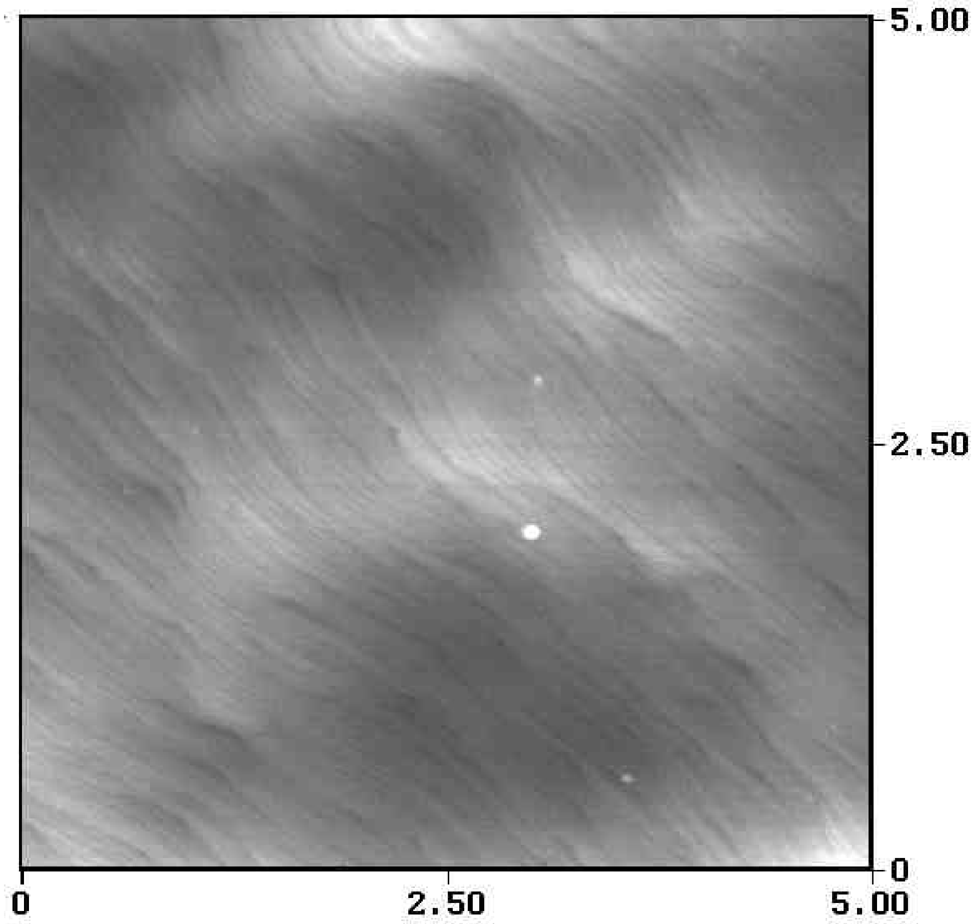


Observe the granularity in the GaN. Grains appear better aligned.



AlN film has edge dislocations, but few screw dislocations

AFM of GaN Grown on “Porous” AlN on SiC



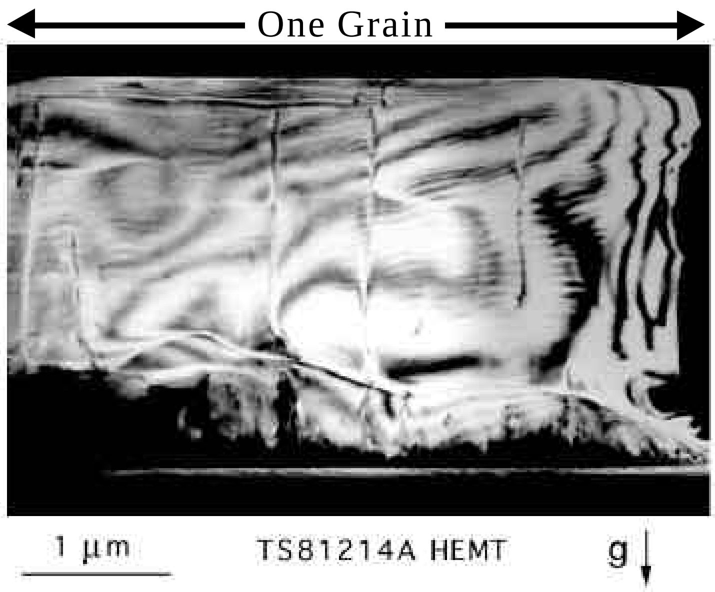
Compared to GaN growth on sapphire, the GaN growth on SiC shows more long range order of GaN atomic layers. This implies a significantly lower concentration of dislocations having a screw component. In TEM the GaN grains are better aligned on SiC.

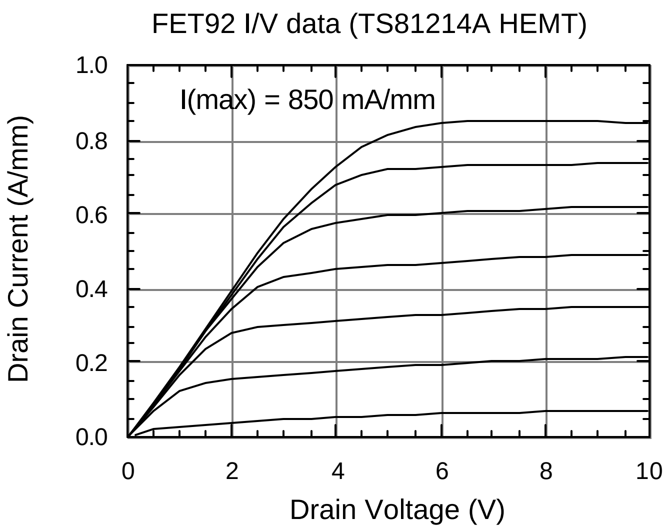
Better GaN grain alignment and fewer screw dislocations
Electron mobilities are > 600 cm^2/Vs in Si doped films
and > 1000 cm^2/Vs in AlGaN/GaN HEMT layers

Electrical Properties of GaN on “porous” AlN on SiC

Run	Si (sccm)	Temp	n x 10^{17}	mobility
		Bulk Si Doped		
2K0714A	0.30	300K	6.64	416
2K0808	0.10	300K	2.38	574
2K0808	0.10	77K	0.64	511
2K0808	0.10	300K	3.36	620
2K0808	0.10	77K	1.00	671
2K0817	0.05	300K	2.01	626
2K0817	0.05	77K	0.52	695
		AlGaN/GaN	HEMT	
2K0810*	-	300K	1.15×10^{13}	1030
2K0810*	-	77K	1.21×10^{13}	1900

FY99 R&D Accomplishments: Control of GaN Microstructure and Defects for Improved Device Performance





- MOCVD material growth optimized for large grain size (> 5 µm) highly resistive GaN, using interactive XTEM & Hall analyses
- AlGaN/GaN interface roughness of 5-10Å measured in XTEM
- $Al_{0.3}Ga_{0.7}N$:Si/GaN HEMT structure grown reproducibly, yielding
  - 300K: $n_{sheet} = 1.2 \times 10^{13}$ cm^{-2}, $\mu = 1500$ cm^2/Vs
  - 77K: $n_{sheet} = 1.3 \times 10^{13}$ cm^{-2}, $\mu = 4000$ cm^2/Vs
- GaN buffer resistivity = 10^5 Ω-cm
- Drain lag eliminated from fabricated devices
- Current collapse reduced in operating devices
- Pulsed power output of 6 W/mm observed in devices fabricated on this material